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14. ABSTRACT

In order to better understand the operating characteristics of a capillary discharge based electrothermal pulsed plasma source, a variety of ignition techniques were investigated to determine performance effects and viability in a real system. Discharge current profiles along with thrust and specific impulse measurements were obtained to take a detailed look at ignition caused by an exploding wire, the Paschen breakdown of gas, and a surface flashover caused by the addition of a third electrode. Experimental testing showed that there are only slight performance differences between the three techniques, however, the surface flashover ignition method is currently the best option for adapting the capillary discharge to space applications due to reliable and repeatable operation. Capillary discharge plasma sources utilizing the surface flashover ignition method showed propulsion efficiencies of 8-18% within an Isp range between 350 and 650 s with no nozzle expansion or material optimization. While these numbers do not match performance predictions in work by Burton, it is believed that material optimization and the addition of an expansion nozzle will exceed all previous experimental efficiencies. Additionally, the development of the surface flashover ignition system has provided important insight into the response of capillary discharges to ignition conditions and techniques.

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The Effect of Ignition techniques on a Capillary Discharge Based Pulsed Plasma Thruster

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In order to better understand the operating characteristics of a capillary discharge based electrothermal pulsed plasma source, a variety of ignition techniques were investigated to determine performance effects and viability in a real system. Discharge current profiles along with thrust and specific impulse measurements were obtained to take a detailed look at ignition caused by an exploding wire, the Paschen breakdown of gas, and a surface flashover caused by the addition of a third electrode. Experimental testing showed that there are only slight performance differances between the three techniques, however, the surface flashover ignition method is currently the best option for adapting the capillary discharge to space applications due to reliable and repeatable operation. Capillary discharge plasma sources utilizing the surface flashover ignition method showed propulsion efficiencies of 8-18% within an I_{sp} range between 350 and $650\,s$ with no nozzle expansion or material optimization. While these numbers do not match performance predictions in work by Burton, it is believed that material optimization and the addition of an expansion nozzle will exceed all previous experimental efficiencies. Additionally, the development of the surface flashover ignition system has provided important insight into the response of capillary discharges to ignition conditions and techniques.

I.   Introduction

CAPILLARY discharges are predicted to have high propulsion efficiencies over an optimal specific impulse range for many earth-orbiting missions.[1] Electric propulsion systems are commonly categorized into three classes: electrothermal, electrostatic, and electromagnetic according to their dominant acceleration mechanism.[2] In general, the class of continuous electrothermal thrusters has demonstrated high thrust efficiencies at specific impulses somewhat less than $1000\,s$, but their thrust efficiency drops precipitously at specific impulses approaching $1000\,s$ due to materials limitations and frozen flow losses. In contrast, electrostatic and electromagnetic thrusters have demonstrated high thrust efficiencies at specific impulses somewhat greater than $1000\,s$. Once again, however, as the specific impulse approaches $1000\,s$ (this time from $> 1000\,s$) their thrust efficiency continuously decreases due to the increasing relative importance of the ionization cost. A pulsed electrothermal thruster could potentially operate efficiently over the entire range of specific impulses from $1000\,s$ to $3000\,s$.[3,4]

Predictions from work on capillary discharges performed by Burton indicate the possibility of achieving a thrust efficiency exceeding 70% over the range of specific impulses from $1000\,s$ to $3000\,s$.[3] Using a capillary as

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the basis for a pulsed plasma source is inherently efficient due to a high dimensional ratio ($length/diameter$). The primary mechanism for energy transfer within the capillary is radiation and the capillary design ensures that the majority of emitted radiation will be absorbed by the propellant walls. Burton's high efficiency predictions were also supported through analysis of the 3-body ion combination rate[5] and the resulting mean free path for recombination within discharge plasma conditions. Burton calculated a mean free path that was significantly less than the length of his nozzle predicting that flow would be in Saha equilibrium and ionization cost would be completely recovered generating high efficiencies.[3] Burtons work did not reach predicted performance levels but tests did show sensitivity to ignition.

Ignition experiments being conducted at AFRL use a nozleless capillary discharge and due to this, performance levels are less than Burton's maximum experimental efficiency of 56%.[4] Previous wire ignition testing has shown that the ignition properties of a capillary discharge can have a great effect on plasma conditions.[6] However, a one dimensional mathematical model developed in parallel with the AFRL capillary discharge pulsed plasma source based upon previous work by Edamitsu[7] predicted little change in discharge characteristics when varying ignition parameters. The incongruity between previous experimental work,
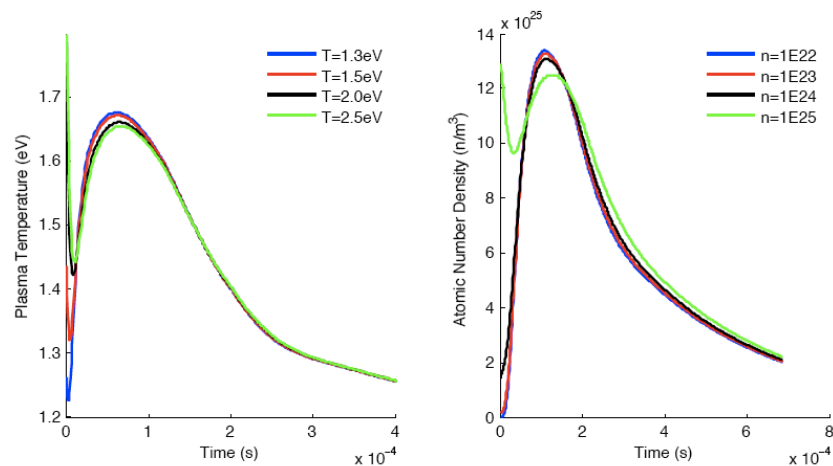
Figure 1. Effects of varying initial plasma temperature and number density as predicted by one dimensional mathematical model showing little change in primary capillary discharge characteristics

current performance numbers, and the smooth profiles seen in Fig. 1 warranted an investigation into alternative ignition techniques and three different ignition methods have been studied at AFRL in response. Wire explosion, Paschen gas breakdown, and a surface flashover caused by a third electrode were all implemented as a means to strike a primary capillary discharge and their effects on performance were characterized.

The majority of previous work with capillary discharges has been conducted employing a wire ignition system. This ignition system uses a thin wire connecting the anode and cathode within a capillary and the explosion of this wire creates the charged particles necessary for electrical breakdown of the primary discharge. While this method is reliable, there are key problems that necessitate further development for use in space applications. Due to the chaotic nature of wire breakdown and vaporization,[8] the initial plasma forming conditions within the capillary can vary from shot to shot. Previous wire ignition testing at AFRL has shown a dual mode of operation in which discharges switch from a high current quick pulse mode to a low current long pulse mode seemingly at random and research indicates that this is an effect of the ignition method itself.[9] Another key issue with wire ignition is the presence of vaporized wire mass within the plasma making it difficult to measure the thrust characteristics from purely ablated material. Finally, the physical aspect of replacing the ignition wire after every pulse renders this ignition method unsuitable for adapting the capillary discharge to spacecraft propulsion applications.

An alternative ignition method utilizes the Paschen breakdown of a gas to ignite a capillary discharge. Fine tuning the electrode gap distance and ambient pressure results in a set breakdown voltage within the capillary. Paschen concluded that breakdown voltage can be described by the equation

$$V = \frac{a(pd)}{ln(pd) + b} \tag{1}$$

Where V is the breakdown voltage in volts, p is the pressure in atmospheres and d is the gap distance in meters.[10] The constants a and b depend upon the composition of the gas and for air at standard atmospheric conditions $a = 43.6 \times 10^6$ and $b = 12.8$. This ignition method allows for repeated capillary discharges without the need for a manual reload of the ignition system. However, it is highly sensitive to atmospheric conditions and requires fine control of both pressure and humidity for repeatability.

A third option studied for ignition was the use of a surface flashover created by a third electrode. By including a third electrode within the capillary, a small surface flashover near the cathode can be reliably generated creating an electric field disturbance as well as ionized material. During the flashover spark, neutral and charged particles are generated[11] creating a conductive path for the primary discharge. Since the ignition methods for the flash over and the main discharge are very similar this can be thought of as a smaller capillary discharge igniting a larger one.

II. Experimental Setup

II.A. Metrics of Comparison

To compare the effects of these ignition methods the primary metric studied was current profiles collected during thruster firings. These profiles provide a clear window into the operating characteristics of the capillary discharge describing both peak power levels as well as the discharge characteristics. Additionally, the impulse (I), specific impulse (I_{sp}), and propulsive efficiency (η) of the plasma source were measured for both the Paschen and three electrode ignition systems by employing a torsional mass balance thrust stand as described in work by Ketsdever.[12] Impulse can be measured directly from the thrust stand and I_{sp} can be determined through before and after mass measurements using a scale. Propulsion efficiency is

$$\eta = \frac{E_{thrust}}{E_{electrical}} \tag{2}$$

Where E_{thrust} is the total thrust energy and $E_{electrical}$ is the simple electrical energy applied to the thruster. Thruster performance data was not collected for wire ignition testing due to the difficulties imposed by the presence of wire mass in the ejected plasma. Ejected wire mass can be equal to the ablated material from the capillary which poses difficulties in the measurement of I_{sp}.

II.B. Thruster Configuration

To accommodate the three ignition systems studied, slightly different capillary discharge housings were developed. The housings all retained a constant capillary profile, utilizing a $4\,mm$ ID $6\,mm$ OD polyethylene tube inserted into a housing made from a steel or aluminum $6\,mm$ ID cylinder. An anode rod was inserted into one end of the polyethylene tube and the other end was then press fit against a circular tungsten or steel cathode.

As can be seen in Figures 2-4, common design elements allowed for varying discharge lengths of $40 - 100\,mm$ simply by moving the anode rod within the capillary tube. Once a desired length was reached, the housing was sealed around the anode creating a compression fit.

For wire ignition testing, a thin aluminum wire was connected between the anode and cathode through slip fitting one end against the anode rod and tightening the other end into the cathode assembly. Initial discharge through this wire caused it to explode facilitating ignition of the primary discharge. Paschen breakdown testing eliminated this wire and the anode and cathode were simply inserted into the capillary as shown in Fig. 3 utilizing the adjustment of pressure and distance to create the appropriate conditions for ignition. The surface flashover method placed a small electrode and insulating ring made of polyethylene
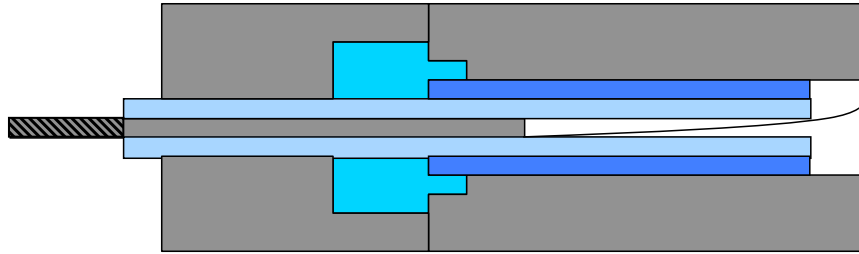
Figure 2. Schematic of the capillary discharge housing for wire ignition testing showing a thin ignition wire between the anode and cathode.
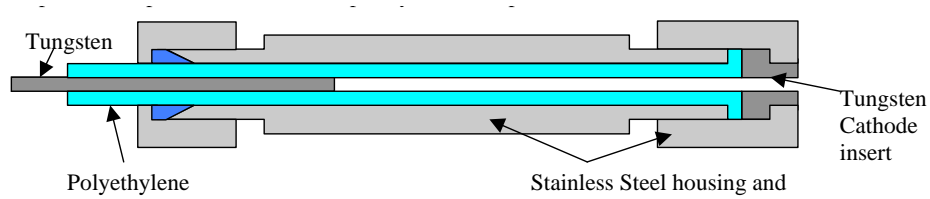

Tungsten

Polyethylene

Tungsten Cathode insert

Stainless Steel housing and

Figure 3. Schematic of the capillary discharge housing for Paschen breakdown testing.

Anode

Cathode

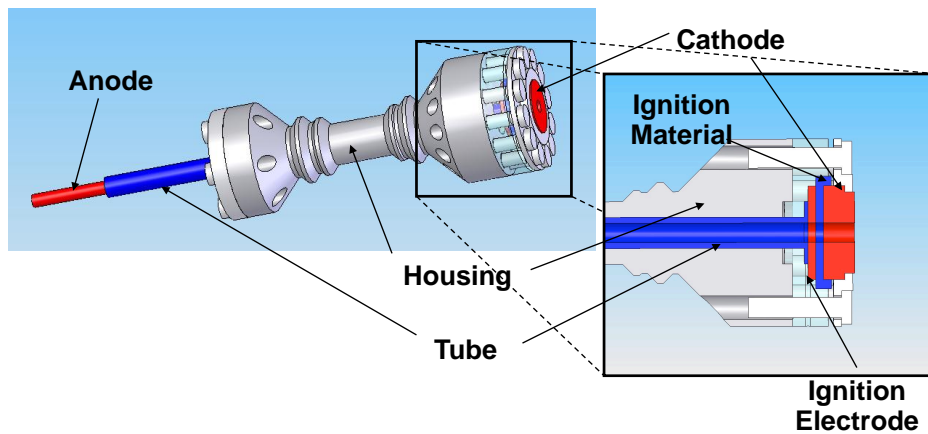Ignition Material

Housing

Tube

Ignition Electrode

Figure 4. Schematic of the capillary discharge housing for surface flashover ignition showing the placement of the third electrode.

between the capillary exit and the tungsten cathode. This third electrode was given a high voltage pulse from a TTL triggered transformer and a surface flashover was created from the third electrode to the cathode. All three ignition methods required small changes to the device, however, a constant capillary profile within the polyethylene tube was maintained.

II.C. Circuit and Diagnostics

All testing of the bare plasma source took place in the ARFL capillary discharge test facility and a LRC circuit was used to drive the capillary as described in previous work by Cambier.[9] A single $500 \mu F$ General Atomics capacitor was connected in series with a nominally $10 \, \mu H$ inductor. The parasitic resistance of circuit was shown experimentally to range of between $24 \pm 1 \, \mu\Omega$ and $91 \pm 5 \, \mu\Omega$. It was also experimentally determined that the circuit itself had an inductance of $7 \pm 0.4 \, \mu$H and the inductor used had an average inductance of $13 \pm 0.7 \, \mu$H.

The LRC circuit was switched using a high-power Silicon-controlled Rectifer (SCR or Thyristor) triggered through a TTL line. A desktop PC running Natinoal Instruments LabView software and a PXI data acquisition system (DAQ) controlled all timing as well as relevant circuit components. In the case of the surface flashover ignition system a computer controlled TTL line triggered the high voltage transformer and power supply used to create the ignition spark.

Current profiles were measured through the use of commercial Powertek Rogowski coils placed at the junction between the LRC circuit and the capillary discharge. Additionally, Ross Engineering high voltage probes were used to measure potential at both the capacitor bank and the power connection to the plasma source. Both of these devices were sampled at $2.5 \, MHz$ utilizing the PXI DAQ system.

As a baseline, thrust measurements for the stand alone plasma source were taken for both Paschen and three electrode ignition tests utilizing a torsional mass balance thrust stand. Based upon previous work by Ketsdever,[12] the system was redesigned and optimized for use with the capillary discharge PPT. The resulting stand had a time resolution on the order of $1 \, \mu$s and was capable of measuring total impulses up to $150 \, mNs$ with a resolution of $0.4 \, mNs$.[13] The thrust stand was calibrated through the use of computer controlled electrostatic combs as described in work by Selden.[14] Due to the comparatively large forces imparted by the capillary discharge, the electrostatic combs described by Selden were rebuilt and scaled up to provide a maximum force of $5x10^{-2} \, N$.[13] The thrust stand diagnostic system and electrostatic combs can be seen in Fig. 5.
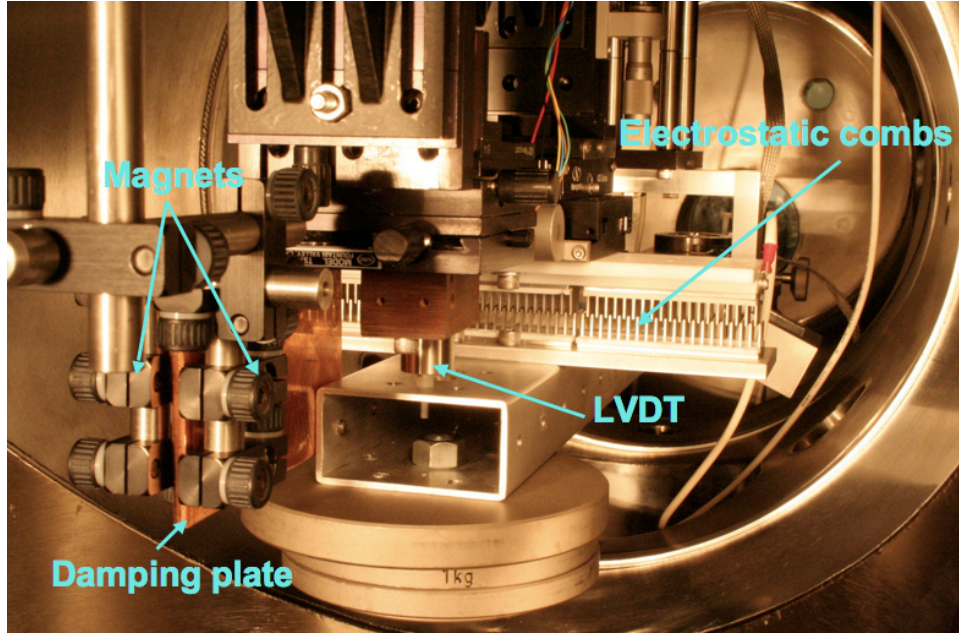
Figure 5. Photograph showing calibration combs, thrust stand dampening system, and LVDT position sensor as mounted on the experimental thrust stand within the AFRL capillary discharge vacuum chamber

III.   Results

A full test matrix was run for all three ignition methods using capillaries 4, 6, 8, and $10\,cm$ in length at discharge voltages of 2000, 2250, 2500, 2750, and $3000\,V$. Wire ignition tests were conducted at atmospheric pressure ($\approx 690\,Torr$), Paschen breakdown pressures varied between 0.1 and $50\,Torr$ depending on the necessary P-d value for ignition and surface flashover was conducted between 10^{-4} and $10^{-5}\,Torr$. For all length-voltage combinations tested with the Paschen and three electrode ignition methods, the capillary tube, anode, cathode and housing were weighed, assembled and installed within the experimental apparatus. Five discharges were performed and the plasma source was again disassembled and weighed to determine a statistical average mass loss for each of the five shots. Additionally, when selecting pressures for Paschen testing the vacuum chamber was pumped down to the limits of the roughing pump ($20\,mTorr$), refilled with dry nitrogen, and pumped back down to the desired pressure creating a uniform environment for all trials.

Figure 6 displays current traces for all capillary lengths at $2500\,V$ and in most cases current profiles look similar for all ignition methods. It can also be seen that decreasing capillary length results in increasing current values. Wire ignition resulted in the highest peak currents except for in $10\,cm$ capillaries. Flashover ignition displayed intermediate current peaks, and Paschen breakdown ignition resulted in the lowest current values. Additionally wire ignition traces show initial current spikes during ignition wire explosion.

At $4\,cm$, current profiles are distinctly similar, however, with increasing capillary length extinction characteristics and pulse lengths began to differ. As capillary lengths were increased, Pacshen breakdown tests began to exhibit long tail extinction which lasted from $100\,s$ of μs to $1ms$. These tails are seen clearly in the $8\,cm$ capillary data in Fig. 6 and were intermittent throughout Paschen testing. Wire ignition current profiles vary dramatically with increasing length and $10\,cm$ wire ignition discharges do not follow the current profiles of the alternative ignition methods.

Figure 7 shows the occurrence of dual mode operation during wire ignition testing as described in previous work at AFRL.[9] Both data sets in Fig. 7 were taken at identical conditions, however, Fig. 7 Plot (b) shows thruster operation in a high current (HC) mode producing larger peak current values and slightly smaller pulse widths. The low current (LC) mode which is seen in Fig. 7 Plot (a) resulted in longer pulses with lower peak values. Dual mode operation occurred at random throughout testing, however, there were no

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intermediate operations between the low current and high current discharges. Operation in the HC mode was never observed during 10cm capillary testing and occurred with increasing frequency as capillary length decreased occurring in $\frac{2}{5}$ of tests at 5 and $6\,cm$ and $\frac{3}{5}$ of tests at $4cm$. LC mode test profiles matched Paschen and three electrode testing and were thus utilized for all comparison.

Paschen breakdown ignition testing produced initial values for I, I_{sp}, η. These three parameters were compared as a function of total pulse energy determined through analyzing the voltage and current profiles provided by the high voltage probes and Rogowski coils respectively. As can be seen in Fig. 8 Plot (a), total impulse increased with increasing energy ranging from $0.02\,mNs$ at $400\,J$ to $0.1\,mNs$ at $2000\,J$. I_{sp} measurements are sporadic due to significant mass loss from erosion of the anode and cathode. The quantity of mass loss from the electrodes often approached 50% of the total mass loss for a given firing. Figure 8 Plot (c) shows that the propulsion efficiency for Paschen breakdown testing raged between 7 and 17% including mass loss from electrode erosion.

Performance data for surface flashover ignition, as shown in Fig. 9, showed greater repeatability and more reliable trends. As with Paschen breakdown ignition, increasing the total energy resulted in higher impulses ranging from $0.03\,mNs$ at $600\,J$ to $0.12\,mNs$ at $2000\,J$. Figure 9 Plot (b) shows that with increasing energy I_{sp} decreases. Adittionally at a given energy level, I_{sp} decreases with decreasing capillary length ranging from $650\,s$ at $600\,J$ with a $8\,cm$ capillary to $350\,s$ at $2200\,J$ with a $4\,cm$ capillary. Efficiency values for three electrode ignition ranged between 8 and 18% including mass loss due to electrode erosion. Figure 9 shows a decrease in efficiency corresponding with either a decrease in capillary length or an increase in total energy. However, 8cm capillary data shows an increase in efficiency as discharge energy increases.

IV. Discussion

In most cases, current profiles for all methods were similar in shape. The wire ignition, despite the additional wire material added to the plasma, was relatively consistent with other ignition techniques. For all methods peak discharge currents increased as capillary length decreased. This trend is a function of conditions within the plasma column inside the capillary. Since the resistivity of the plasma column is a function of length, a shorter discharge will decrease in resistance resulting in larger peak currents.

The differences in current profiles between different ignition techniques at a given length are result of the ignition plasma characteristics. The lowest peak current values were seen with Paschen breakdown ignition as this method causes a breakdown of the low pressure gas within the capillary. The resulting plasma created is initially high density and low temperature which results in a higher resistance and a comparatively low current discharge. Surface flash over ignition, which was operated at a lower vacuum, does not have as much material within the capillary during initial plasma formation and thus the plasma column that forms is less dense and at a higher temperature. These conditions result in lower resistivity causing three electrode ignition to display higher currents than the Paschen method. The fact that wire ignition had the highest peak currents suggests that an exploding wire results in a plasma column that is hot but not necessarily dense. Since the profiles for wire ignition are similar to the other ignition methods, it is also assumed that when the ignition wire explodes it creates a small region of hot plasma before the main plasma column forms leaving the majority of wire material to be ejected from the capillary without fully melting, vaporizing, or disassociating. Despite these differences, performance characteristics were similar for all ignition techniques. The quickness with which the primary discharge forms mitigates irregularities caused by ignition methods and predictions stating ignition played a key role were made after witnessing irregularities in wire ignition tests.

The effects of wire decomposition also support the presence of dual mode operation seen exclusively in wire testing. Due to the chaotic nature of an exploding wire, initial conditions change for each test. If the wire heats and breaks down at a single point, a conductive plasma is not instantly formed and the uneven breakdown results in small pockets of hot plasma. The resulting discharge creates a plasma column with a higher resistivity and the low current mode of operation is witnessed. In the case of the high current mode, the ignition wire breaks down evenly filling the capillary with a highly ionized conduction path for the main discharge. A higher $\frac{di}{dt}$ results from this favorable conduction medium and the high current mode of operation is witnessed. The HC mode occurs with greater frequency in shorter capillaries because it is

easier for uniform wire breakdown across shorter distances.

As the capillary length increased, wire ignition testing deviated from the standard current profile resulting in an elongated discharge with decreasing current values. These discrepancies are a result of background pressure effects. As can be seen in Fig. 7, $10\,cm$ data shows there is a slight hump present during the main discharge current rise in addition to the initial spike due to wire explosion. Brief testing revealed that as background pressure is decreased, this abnormality is removed and as pressure drops below $0.5\,mTorr$ the initial hump is no longer present and there is a consistent $\frac{di}{dt}$ through the entire ignition process.

The long tail extinction witnessed during Paschen testing is an effect of secondary ablation upon the outer walls of the capillary tube. Radiation penetrating the capillary was reflected back from the walls of the housing causing exterior capillary ablation. It is important to note that secondary ablation primarily effected the extinction of the device and did not affect the current rise or peak power of the main discharge. Developments in the capillary housing preceding surface flashover ignition testing eliminated this problem.

Thrust performance data for both Paschen breakdown and surface flashover ignition testing both show similar trends relating impulse to power, however, only surface flashover testing produced reliable data for I_{sp} and η. In addition to housing advancements made prior to surface flashover testing which mitigated electrode erosion, differences in experimental technique also added to three electrode reliability. In contrast to the Paschen and wire tests, all testing of the surface flashover system was completed using pre-discharged capillaries. It was observed that the first firing of a new tube could vary greatly from subsequent testing. To eliminate this problem, all tubes were fired two to three times, removed from the system, reweighed, and reinserted into the device. Preconditioning had a very small effect on the inner diameter of the new capillary and no effects were seen in the discharge characteristics except for the elimination of abnormalities seen in new tube firings. This resulted in more accurate statistical average mass loss values and the repeatable data seen in Fig. 9.

Due to similar current profiles and similar performance numbers across all three ignition methods, it can be concluded that the ignition method has only a slight impact upon the performance of a capillary discharge. Additionally, all ignition methods begin to pose problems at longer capillary lengths which is problematic due to data indicating increasing efficiencies for longer capillaries. This was especially true with the surface flashover ignition method as reliability dropped below acceptable levels when using capillaries $10\,cm$ in length. Despite a lack of distinct performance differences between methods, the surface flashover ignition system still differentiates itself as the best option. The reliability and repeatability seen in surface flashover ignition data are essential elements to adapting the capillary discharge for a spacecraft thruster. These same features coupled with ease of use have made surface flashover ignition the chosen technique for nozzle testing and development of the capillary discharge thruster at AFRL.

V.   Conclusion

An investigation into ignition methods at AFRL has evaluated the performance and discharge characteristics of a capillary based pulsed plasma source ignited using three different ignition techniques. Overall performance and circuit characteristics proved to be very consistent over the range of methods and large deviations were only seen during wire ignition testing. It is speculated that all ignition techniques, including the low current mode of the wire ignition, are in fact a Paschen-type breakdown in which conditions are created within the capillary that are ideal for electron cascade down the entire capillary length. In the high current wire ignition mode, it is believed that a more instantaneous and fully ionized plasma column is created by the chaotic nature of wire explosion which allows charge to move more rapidly and immediately. This could explain the higher current mode and its greater likelihood at shorter lengths. The tests conducted here have proven that three electrode ignition is reliable and repeatable without the need for manual replacement of an ignition wire or fine atmospheric control rendering it the best option currently available for adapting the capillary discharge to space propulsion applications. The developed three electrode ignition system has laid the groundwork for future capillary testing at the AFRL, including an investigation into the effects of nozzle expansion and alternative capillary materials, to constitute a full capillary discharge thruster.

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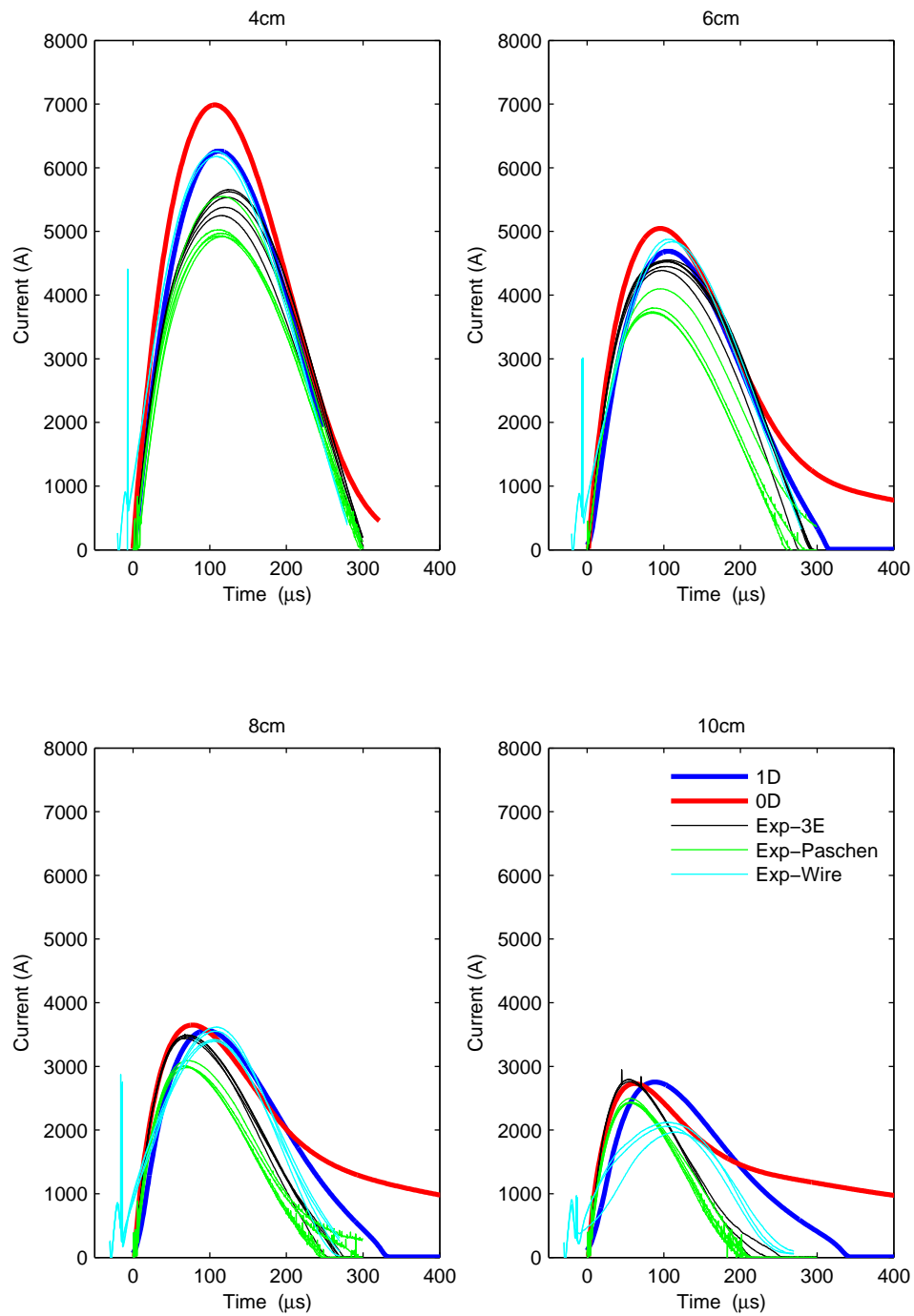
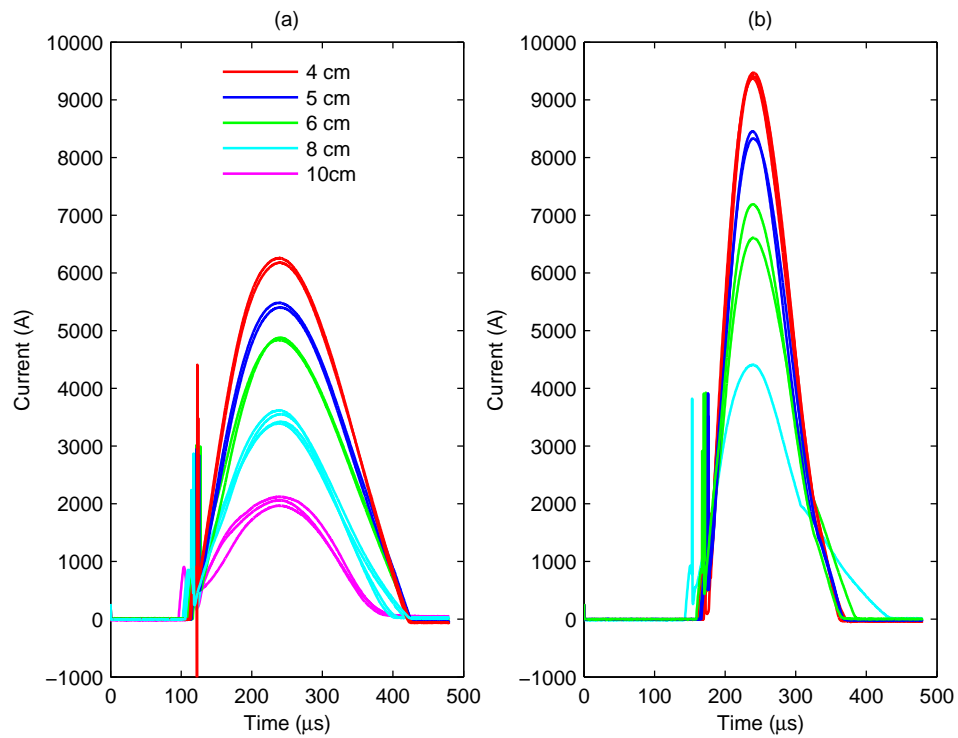**Figure 6. Comparison of discharge currents for three ignition methods using 4,6,8 and 10cm capillaries at 2500V**

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Figure 7. 2500V capillary discharge currents for varying lengths using wire ignition
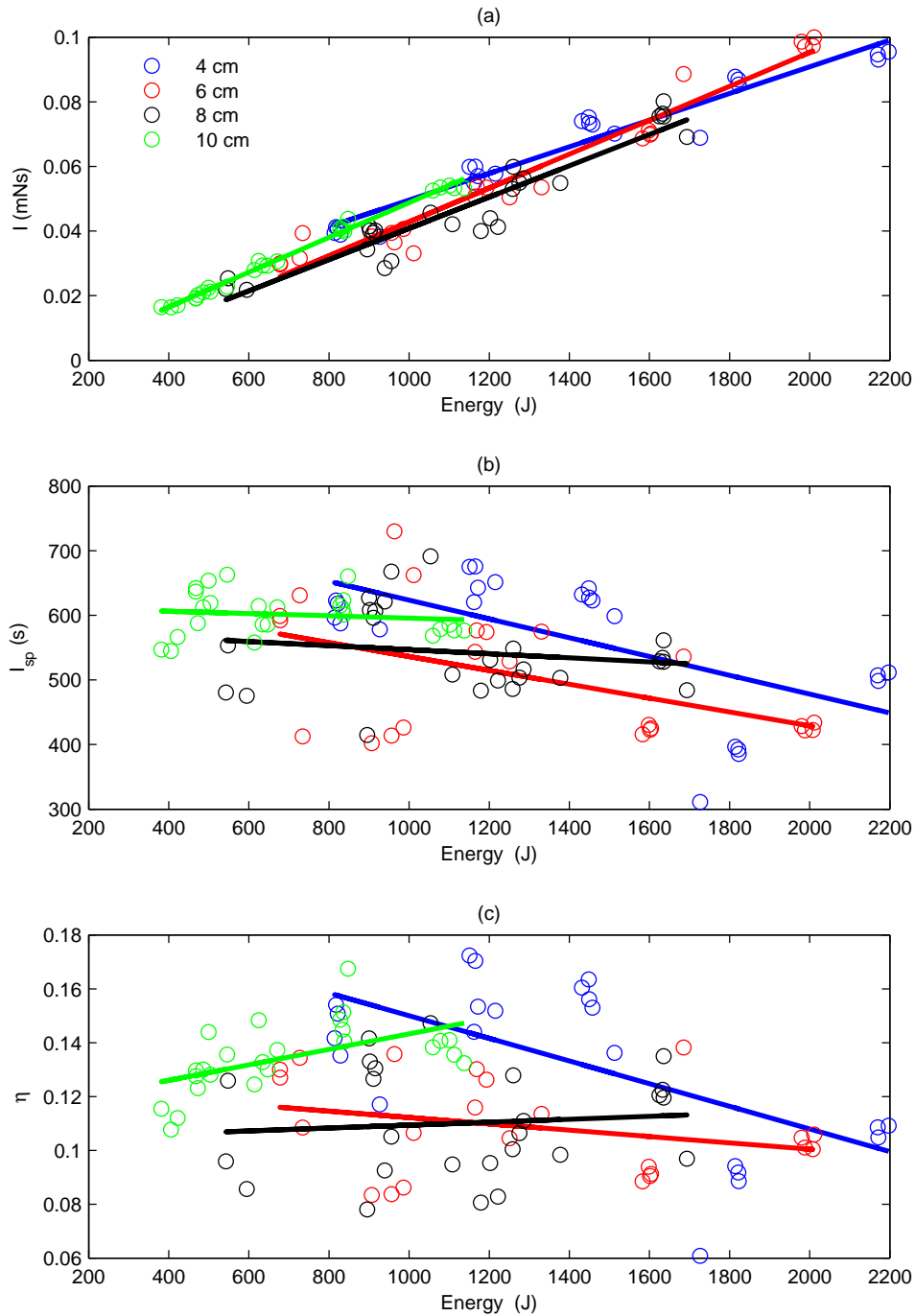
Figure 8. Impulse (a), Specific Impulse (b), and Propulsion Efficiency (c) as a function of input energy for 4, 6, 8 and 10cm **capillaries using Paschen breakdown ignition**
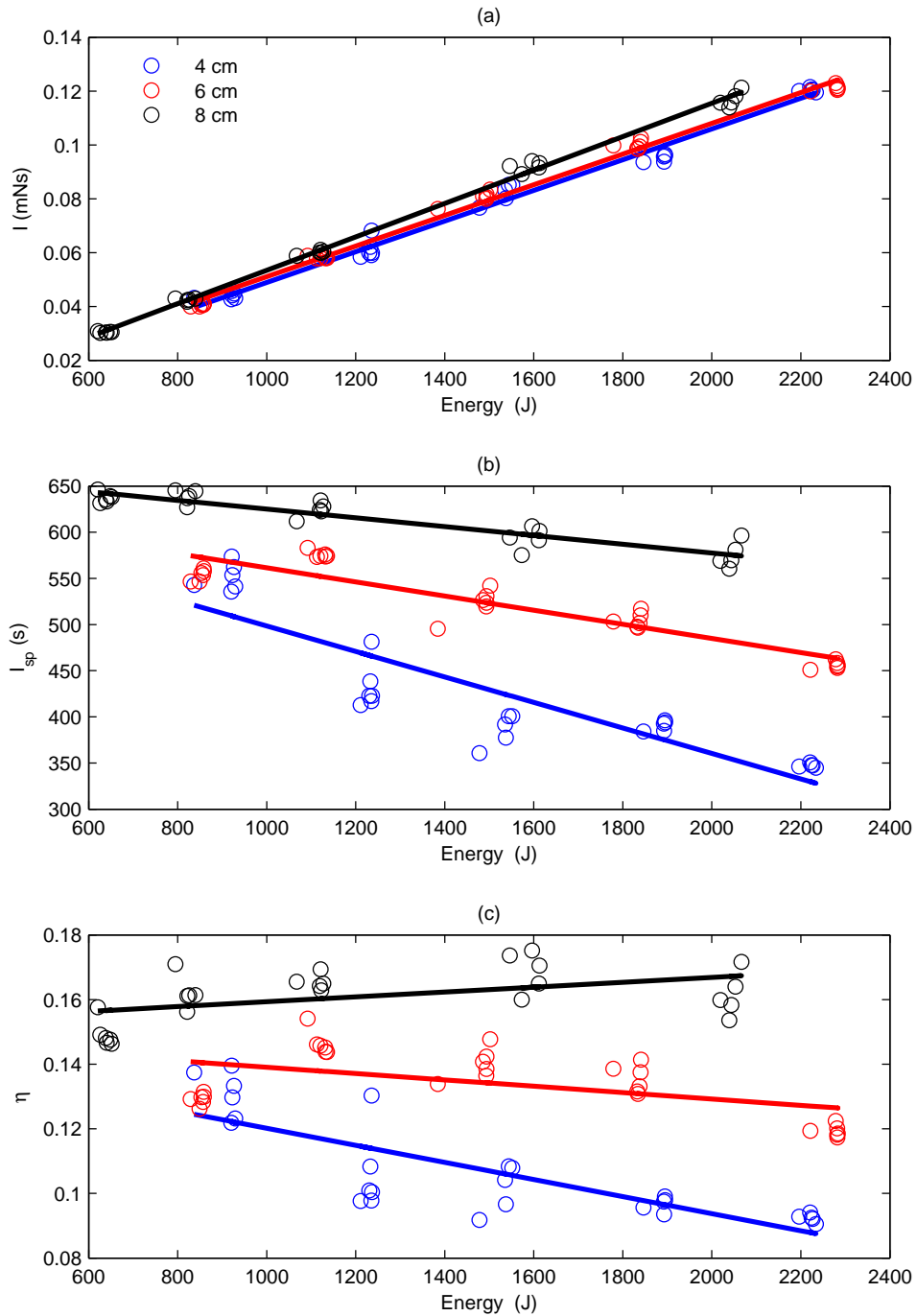
Figure 9. Impulse (a), Specific Impulse (b), and Propulsion Efficiency (c) as a function of input energy for 4, 6 and 8cm **capillaries for surface flashover ignition**

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